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PHYSIOLOGICAL FACTORS AFFECTING PERFORMANCE IN ELITE DISTANCE RUNNERS

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ABSTRACT

Running distances from 3000 m to the marathon (42 195 m) are events dominated by energy contribution of the aerobic energy system. The physiological factors that underlie success in these running events are maximal oxygen uptake ($\text{VO}_{2\text{max}}$), running economy (RE), the utilization of the maximum oxygen uptake ($\%\text{VO}_{2\text{max}}$) and velocity at the anaerobic threshold (vAT). $\text{VO}_{2\text{max}}$ for distance runners competing on an international level has been between 70 and 87 ml/kg/min in men, and between 60 and 78.7 ml/kg/min in women, respectively. Due to lack of air resistance, laboratory testing of RE and vAT are recommended to be conducted on treadmill with 1% slope. $\%\text{VO}_{2\text{max}}$ are in most studies expressed as the average fractional utilization of $\text{VO}_{2\text{max}}$ at vAT. Much of the current understanding regarding the response to exercise is based on studies of untrained and moderately trained individuals. To use this knowledge to give training recommendations to elite runners is hardly valid. Researchers should therefore exercise caution when giving training recommendations to coaches and elite distance runners based on limited available research.

Keywords: $\text{VO}_{2\text{max}}$; running economy; anaerobic threshold

INTRODUCTION

Long distances from 3000 m to the marathon (42 195 m) are events dominated by energy contribution of the aerobic energy system [10, 64]. Improving performance over these distances has to influence one or more of the physiological factors that underlie success in distance running. Studies

have shown that these physiological factors are maximal oxygen uptake ($\text{VO}_{2\text{max}}$) [21, 25, 49], running economy (RE) [12, 44, 49], utilization of the maximal oxygen uptake ($\% \text{VO}_{2\text{max}}$) [1, 47] and velocity at the anaerobic threshold (vAT).

This brief review is concerned with the available evidence with respect to $\text{VO}_{2\text{max}}$, RE, $\% \text{VO}_{2\text{max}}$ and vAT in elite distance runners.

MAXIMUM OXYGEN UPTAKE ($\text{VO}_{2\text{MAX}}$)

A high $\text{VO}_{2\text{max}}$ is a prerequisite for success in distance running [16, 34, 41, 58]. Legaz-Arrese et al. [35] examined the relationship between $\text{VO}_{2\text{max}}$ and running distances in Spanish elite runners. The study included 190 runners (137 men and 53 women) who competed at national and international level in distances from 100 m to the marathon. The runners' $\text{VO}_{2\text{max}}$ increased with increasing competition distance from 100 m to 3000 m. Among runners who competed in distances from 3000 m to the marathon, the variations in $\text{VO}_{2\text{max}}$ were small. The authors concluded that a high $\text{VO}_{2\text{max}}$ is necessary to perform at national and international level in race distances from 3000 m to the marathon [35]. However, substantial variation in $\text{VO}_{2\text{max}}$ has also been found among runners who are of the same performance level and who compete over the same distances [12, 26, 59, 68].

A study of Spanish elite male middle- and long-distance runners between 2000 and 2008, shows following average $\text{VO}_{2\text{max}}$ values [54]. 1500 m ($n=23$) 67.4 ± 4.7 ml/kg/min, 5000 m ($n=20$) 71.4 ± 3.9 ml/kg/min and 10 000 m ($n=12$) 71.8 ± 6.7 ml/kg/min. The runners were tested at the start of the training year as part of a screening process.

A study by Legaz-Arrese et al. [34] showed that there was no significant difference in $\text{VO}_{2\text{max}}$ between ten marathon runners and eight 3000 m steeplechase runners at the same relative level of performance. The marathon runners (average time for the marathon 2:12.04) and the 3000 m the steeplechase runners (average best times of 8:37.83) had 81.3 ± 4.0 and 80.5 ± 3.9 ml/kg/min in $\text{VO}_{2\text{max}}$, respectively.

The Nordic male record holder for the 5000 m, at the time writing, had a $\text{VO}_{2\text{max}}$ of 86.7 ml/kg/min at the age of 21 [68]. $\text{VO}_{2\text{max}}$ values of elite Kenyan runners who were tested by Billat et al. [5] in 2002 and who used a training regimen based on moderate training volume and rather high intensity were: men ($n=6$): 78.4 ± 2.1 ml/kg/min, and women ($n=6$): 68.6 ± 1.1 ml/kg/min. These athletes ran 158 ± 19 km/week (men) and 127 ± 8 km/week (women). Average time for 10 000 m was 28:15 min (± 15 s) for men and 32:22 min

(± 35 s) for women. Men ($n=7$) who used a training regimen consisting of higher training volume (174 ± 17 km/week) and somewhat lower training intensity had a slightly lower average $\text{VO}_{2\text{max}}$ (74.7 ± 2.6 ml/kg/min) than the runners who trained more intensively. These runners also performed a little slower over the 10 000 m ($28:54$ min ± 33 s). However, there was an overlap in $\text{VO}_{2\text{max}}$ and performance level among the runners in the two groups.

The outstanding Norwegian female distance runner Grete Waitz who won the World Cross Country Championships five times (1978–81 and 1983) and New York Marathon nine times (1978–1980, 1982–86 and 1988) had, early in her career, a $\text{VO}_{2\text{max}}$ of 73 ml/kg/min [14]. The female world marathon record holder at time of writing, Paula Radcliffe, measured 70 ml/kg/min in $\text{VO}_{2\text{max}}$ in 2003, the year she set her world record time of 2:15:25 [28].

Norwegian female distance runners ($n=12$) who have represented Norway in Olympic Games or World Championships were tested at the Norwegian National Sports Centre in the period 1996–2010 and had an average $\text{VO}_{2\text{max}}$ of 69 ml/kg/min, ranging from 64.8 to 78.7 ml/kg/min [68]. The former Kenyan record holder, Kipchoge Keino had a $\text{VO}_{2\text{max}}$ of 84.8 ml/kg/min [57]. This value is comparable to former British 10 000 m world record holder Dave Bedford who had a $\text{VO}_{2\text{max}}$ of 85.0 ml/kg/min [3] and former USA record holder Steve Prefontaine who had 84.4 ml/kg/min [53]. Other studies have shown $\text{VO}_{2\text{max}}$ values from 70 to 85 ml/kg/min in men and 60 to 75 ml/kg/min in women who have competed at an international level in long-distance running [46, 59, 62].

RUNNING ECONOMY

Running economy (RE) is defined as the oxygen consumption required for a given submaximal intensity [1, 15, 58]. In the 1930s, Dill et al. [19] found differences in oxygen consumption (VO_2) at a given speed between runners. Since then a number of studies have reported considerable variation in oxygen uptake at submaximal loads among runners with similar $\text{VO}_{2\text{max}}$ [1, 28, 42]. With improved RE runners can maintain a higher speed with the same oxygen uptake.

According to Jones [28], the most common way to test RE is to test the VO_2 at a speed of 16 km/h. To compensate for the lack of air resistance in the laboratory compared to outdoor running, it is recommended to have a treadmill incline of 1% [30]. At this speed the VO_2 of good runners ranges from 45 to 60 ml/kg/min. When RE is expressed in ml/kg/km, 200 is considered

an average. Values below and above 200 ml/kg/km are expressed as good and poor RE, respectively [28].

Weston et al. [70] compared elite runners from East Africa with European elite runners. Running at a speed of 16.1 km/h, average VO_2 was 187.5 and 190 ml/kg/km for east African and European runners, respectively.

A study comparing a group of male Spanish long-distance runners with a group of elite long-distance runners from Eritrea [37] found no significant difference in $\text{VO}_{2\text{max}}$ between the two groups. RE, however, was significantly better among the Eritrean runners. The Eritrean runner who became World Cross Country champion over 12 km in 2007, used only 150 ml/kg/km when he ran at speeds of 17, 19 and 21 km/h. This is the lowest VO_2 reported at these speeds [38].

In a study by Rabadan et al. [54] test-data for Spanish male middle- and long-distance elite runners ($n=72$) from 2000 to 2008 are reported and provide the following values for RE. 1500 m runners ($n=25$): 190.7 ± 31.7 ml/kg/km, 5000 m runners ($n=20$): 219.7 ± 37.9 ml/kg/km, and 10 000 m runners ($n=12$): 203.1 ± 31.5 ml/kg/km. These runners were tested on a treadmill with a 1% incline.

Good RE is often reported among experienced long-distance runners who, over time, have run many kilometres per week [52, 68]. The RE for Paula Radcliffe, the female world record holder for the marathon distance at the time writing, gradually improved from 204 ml/kg/km in 1992 to 175 ml/kg/km in 2003. RE was tested on the treadmill running at a speed of 16 km/h and an incline of 1% [28]. Her $\text{VO}_{2\text{max}}$ was relatively stable during this same period. Jones [28] concluded that many years with high training volume had had a positive effect on her RE. He also believed that strength training could have helped to improve RE. In a vertical jump test, she improved from 29 cm in 1996 to 38 cm in 2003. Other studies have also indicated that strength training can improve RE and performance in distance runners [51, 58].

Studies have also shown improvements in RE in runners as a result of interval training [7, 22, 32] and training intensity at the anaerobic threshold [60]. However, some studies did not find any improvement in RE after a period of endurance training [33, 50]. The reason for this discrepancy might be that these studies took place over too short a period to affect RE. Johnston et al. [27] examined the effect of 10-week strength training on a range of physiological variables. Subjects were endurance trained female runners with no previous experience of strength training. The training resulted in a strength increase of 24% in exercises involving muscle groups in the upper body, and 34% for exercises where the legs were used. During the 10-week training

period there were no changes in body weight, lean body mass, percentage body fat or muscle circumference. The training did not result in any significant increase in $\text{VO}_{2\text{max}}$, but the RE at a given submaximal load improved by 4%. The researchers suggested that the increased strength resulted in greater mechanical efficiency and improved recruitment pattern of the motor units.

Practical experience and research indicate that RE is, to some extent, dependent on training intensity [2, 22, 29, 48]. Daniels and Daniels [17] performed a comparative study of middle-distance runners and marathon runners. The purpose was to see if there were differences in RE between the two groups of runners when running at 1500 m pace and marathon pace. The results showed that marathon runners had better RE than middle-distance runners when running at marathon pace. However, at 1500 m pace RE was best among the middle-distance runners. Differences in running speed during training and competitions may explain these findings, and underline the importance of training at specific race pace [2, 56]. This may also be the reason why endurance training with high intensity has been reported to have a positive effect on RE in trained athletes [13, 18, 22, 29, 63]. Sjödin and Svedenhag [61] studied the effect of specific strength endurance and speed training for well-trained distance runners. In addition to their normal training regimen, these runners also included either step jumps in a 400 m long asphalt hill or sprint training. Step jump where movement speed was lower than in normal running had the best effect on the RE at a speed corresponding to 4:00 min/km, while sprint training had the best effect on RE at a speed of 3:00 min/km. The runners in the study improved their RE by, on average, 5.1%. Two of the runners who had trained step jumps had a reduced VO_2 of 8% and 12%, respectively, at the speed 4:00 min/km. However, a pace of 4:00 min/km is much slower than competition pace for all race distances from 3000 m to the marathon. Male marathon runners at an international level have a race pace of around 3:00 min/km.

UTILIZATION OF $\text{VO}_{2\text{MAX}}$ (% $\text{VO}_{2\text{MAX}}$)

% $\text{VO}_{2\text{max}}$ is the average percentage of $\text{VO}_{2\text{max}}$ a runner can sustain over a given distance or time [1, 24]. Due to methodological problems related to testing % $\text{VO}_{2\text{max}}$ during competitions, indirect test methods are generally used. The average percentage of $\text{VO}_{2\text{max}}$ a runner utilizes at vAT during a laboratory test is often used as an indirect expression of % $\text{VO}_{2\text{max}}$ [24, 65]. A close correlation is found between % $\text{VO}_{2\text{max}}$ at vAT and % $\text{VO}_{2\text{max}}$ in competitions [31, 65]. Good distance runners can typically maintain running speed at $\text{VO}_{2\text{max}}$ for between five and seven minutes [4, 9]. When the running time

exceeds seven minutes, $\%VO_{2max}$ declines with increasing race distance and duration [58]. This means that $\%VO_{2max}$ is an important factor in longer races such as half – marathon and marathon [47]. Male elite runners and runners at regional level, running the marathon between 2:05 and 3:00 hours, utilize 85–80% of VO_{2max} through a marathon, while runners who have a finish time between 3:25 and 4:00 hours utilize 70–60% of their VO_{2max} [1, 59].

To achieve good performances in aerobic endurance events, the athlete needs to work as close as possible to VO_{2max} [9, 65]. Distance runners at a high level of performance often have a high $\%VO_{2max}$ [65]. When running at a speed corresponding to vAT pace, average $\%VO_{2max}$ in Kenyan male distance runners was a little higher for runners who used a training regimen consisting of high training volume compared to runners using a training regime with slightly lower training volume and higher intensity [5]. The utilization of VO_{2max} at vAT for these two groups were $91.8 \pm 2.5\%$ ($n=6$) and $89.0 \pm 1.2\%$ ($n=7$), respectively. Running at 10 000 m pace, the utilization of VO_{2max} for these two groups was $95.7 \pm 1.9\%$ and $93.7 \pm 1.9\%$, respectively [5]. Coetzer et al. [11] reported 92% fractional utilization of VO_{2max} at a velocity corresponding to 10 000 m pace among runners from South Africa. In a Norwegian study [68], it was found that 12 female long-distance runners at national and international level had a mean $\%VO_{2max}$ at vAT of 86.1% (range 82.1–90.4 %). Among marathon runners of different performance levels, a correlation has been found between $\%VO_{2max}$ at a speed of 15 km/h and marathon time ($r=-0.94$; $p<0.05$) [59]. In homogeneous groups, however, there does not necessarily exist a correlation between $\%VO_{2max}$ and performance [5, 70].

RUNNING VELOCITY AT ANAEROBIC THRESHOLD (VAT)

Although research indicates that lactate production rather delays muscular fatigue than causing it, and that muscular fatigue is caused by factors other than lactate [55], lactate production coincides with muscular fatigue [28, 55]. A strong correlation has been observed between lactate metabolism and performance level in endurance events [29, 39, 69] and the relationship between lactate levels and workloads is therefore frequently used to identify and predict distance running performance [20, 28]. Anaerobic threshold (AT) is often defined as the highest workload during continuous dynamic work, where large muscle groups are used and where there is a balance between production and elimination of lactate [8, 41].

Various criteria and methods have been used to estimate vAT (20), but a correlation between vAT and performance in long-distance running has been consistently observed, regardless of the method used [39, 45, 71]. vAT is a running speed that a well-trained distance runner can sustain for approximately one hour (half marathon pace for elite runners) [8]. Due to various test methods used for testing vAT , it is difficult to specify exact values for vAT matching performance for different distances.

In a Norwegian study [68], it was found that the variables VO_{2max} , RE and $\%VO_{2max}$ explained 89% of the variation in vAT among distance runners at national and international level. In this study, VO_{2max} was correlated with vAT for men ($n=22$). However, amongst the female athletes there was no correlation between vAT and any of the other variables (VO_{2max} , RE and $\%VO_{2max}$) ($n=12$). This was due to large individual differences that, to a certain extent, equalized each other.

In the previously mentioned study of 7 female and 13 male elite Kenyan long-distance runners, Billat et al. [5] used a field test on a synthetic 400 m-track to test VO_{2max} , RE, vVO_{2max} and vAT . The starting speed was set at 14 km/h and 16 km/h for women and men, respectively. Every 3 min the speed was increased by 1 km/h. Between each stage there was 30 s rest during which a blood sample was taken from the fingertip. Lactate concentration was analysed by Lactate Pro LT analyser. Average vAT for women was 16.8 ± 0.8 km/h. Average vAT for the most intensive trained male runners ($n = 6$) with best average 10 000 m time of 28:15 min (± 15 s) was 20.2 ± 0.4 km/h. Men ($n=7$) who used a training regimen consisting of higher training volume and lower training intensity and with an average best 10 000 m times of $28:54 \pm 33$ s, had an average vAT of 19.9 ± 0.4 km/h.

Maffulli et al. [39] reported a correlation between vAT and performance over distances from 5000 m to the marathon. However, there was no correlation between vAT and performance for 800 m and 1500 m. This suggests that large volumes of training influence vAT . Jones [28] also reports an increase in vAT for the female marathon world record holder at the time writing, as a result of many years with high training volume. Lehmann et al. [36] reported increased vAT as a result of more training performed at intensities at vAT pace in distance runners. Other studies have reported increased vAT as a result of more training at velocities above vAT pace [6, 66].

SUMMARY

The research literature indicates that $\text{VO}_{2\text{max}}$ for distance runners competing at an international level has been between 70 and 87 ml/kg/min in men, and between 60 and 78.7 ml/kg/min in women, respectively [28, 46, 59, 62, 68].

RE is often expressed as the VO_2 at a speed of 16 km/h on a treadmill with 1% slope [30]. At this speed, the VO_2 for good runners range from 45 to 60 ml/kg/min [28]. When RE is expressed in ml/kg/km, 200 is considered an average. Values below and above 200 are expressed as good and poor RE, respectively [28]. Among elite runners of the same performance level, an inverse relationship has been found between $\text{VO}_{2\text{max}}$ and RE [43,68]. The average fractional utilization of $\text{VO}_{2\text{max}}$ at vAT pace has been reported to be 86.1 and 84.5% in studies of Norwegian (n=12) [68] and Kenyan (n=7) [5] female elite long-distance runners, respectively. In two groups of Kenyan male elite long-distance runners, average % $\text{VO}_{2\text{max}}$ at vAT was 89.0 and 91.8%, respectively [5]. However, the fractional utilization of $\text{VO}_{2\text{max}}$ was not a factor predicting performance among homogenous groups of Kenyan and Norwegian elite distance runners [5, 68]. Due to lack of air resistance, laboratory testing of elite runners is recommended to be conducted on treadmill with 1% slope [30]. Higher vAT and $\text{VO}_{2\text{max}}$ are reported for long-distance runners than for middle-distance runners [54, 68] even though middle-distance runners typically carry out more intensive training, which has been shown to be beneficial in increasing $\text{VO}_{2\text{max}}$ in recreational runners [23]. Good RE is also reported among long-distance runners as a result of many years with high training volume (many kilometres per week) [28, 68].

When it comes to the training methods best suited to improving the different variables that influence performance among elite distance runners, a review article by Midgley et al. [40] underlines that much of the current understanding regarding the response to exercise is based on studies of untrained and moderately trained individuals. To use this knowledge to give training recommendations to elite runners is hardly valid. Researchers should therefore exercise caution when giving training recommendations to coaches and elite distance runners based on limited available research.

The training methods used by elite distance runners during the last decades have been influenced by training theories that provided success for other outstanding runners, from trial-and-error of coaches and runners themselves, and, to some extent, also by research. Some athletes and coaches have focused on high intensity training and lower training volume, while others prioritized greater training volume with lower intensity. Still others have combined large training volumes with elements of more intensive training.

In a recently published review article [67] examining the training volume and intensity distribution of international level distance runners, international level distance runners were found to run an average of 120–260 km/week. The training volume for 5000 m and 10 000 m runners was typically around 150–200 km/week, while 1500 m runners typically ran 120–160 km/week. High training volume is often a result of many weekly training sessions, and elite runners typically carry out from 12 to 17 running sessions per week. The runners combined these weekly training volumes, of which 70 to 90% is carried out as easy and moderate continuous running, with 2–4 sessions per week at the velocity at the anaerobic threshold (vAT pace), and 1–2 sessions per week above vAT pace during the preparatory period. Runners who competed over distances from 1500 m to 10 000 m reduced the number of sessions carried out at vAT pace and increased the number of sessions at specific race pace in the pre-competition period and during the competition period. The best results for the marathon have been achieved using a “low volume/high intensity-model” (150–200 km/week), as well as via a “high volume/low intensity-model” (180–260 km/week).

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